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FEASIBILITY OF USING LIQUIDS OTHER THAN HYDROGEN FOR THE LIQUID BEHAVIOR TESTS OF THE ZERO-G TEST PROGRAM

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Introduction

The zero-g test program includes a number of supporting analytical studies, as described in reference 2, required to implement more adequately its various phases. The present report is a result of one such study, on the simulation of liquid behavior. This investigation has been necessary not only to assure that a scaled container does not alter the validity of the test data, but also to establish the feasibility of using liquids other than hydrogen. This would result in considerable savings in time and effort in the conduction of the tests, higher reliability of the test equipment, fewer flights and elimination of fire or explosion hazards. The following sections deal at length with the problems of dynamic similarity when such a simulation is attempted for some of the test phases.

Summary

An analytical study was made to determine if hydrogen could be replaced by other liquids in the KC-135 liquid behavior tests. For some of the proposed tests an analysis yielded non-dimensional parameters in which fluid properties played an important role for the achievement of similarity. With other tests, fluid properties did not enter into the problem of similarity.

It was found that a number of liquids could be used for the tests. However, other considerations dominated the selection of test fluids. LN_2 was selected for the sloshing test because similarity could be achieved with lower container accelerations with LN_2 than with other liquids. Because of limited test space, low accelerations are desired. The prime requirement for the coalescence tests is a "wetting" liquid that will rapidly approach it's equilibrium distribution in zero-g. Tests will be conducted with numerous liquids in order that a high reaction rate liquid may be selected for the zero-g test program.

Discussion and Results

An investigation was made to determine if some liquids, other than liquid hydrogen, can be used in the KC-135 liquid behavior tests. The tests to be affected if liquid hydrogen is replaced by another liquid are coalescence, settling, and sloshing.

In general, the criteria used for determining if other liquids could replace liquid hydrogen was to find if the model tests would be dynamically similar to the liquid behavior in the Centaur. For dynamic similarity to be possible the model and Centaur tanks must be geometrically similar. In addition, certain dimensionless numbers, related to the liquid process, must be identical for both model and prototype. These dimensionless numbers are obtained by non-dimensionalizing the equationf of motion which include the continuity and momentum equations.

The investigation showed that for all cases some liquid other than hydrogen could be used. In some instances liquid properties did not enter into the solution. The discussion that follows outlines the approach taken to determine if the model tests can simulate the fluid behavior in the Centaur.

Coalescence Tests. The purpose of the coalescence tests is to simulate distribution of fuel in the Centaur during zero-g with a scale model tank. The simulation is to be carried out with and without multiple surface devices in the model.

It can be demonstrated that the final liquid distribution within the model in zero-g will be similar to the distribution in the Centaur fuel tank if the following is true:

1. Model test liquid is a "wetting" fluid because liquid hydrogen is a "wetting" fluid

2. Model and prototype tanks are geometrically similar

3. Liquid to gas volume ratio of model is equal to prototype

Liquid behavior in a zero-gravity field is dominated by surface tension. From the principle of minimum surface energy (reference 1), the equilibrium or stable configuration of liquid within the tank will be such that the total surface energy within the tank will have a minimum value. Thus, if a liquid is "wetting" (if it will wet the tank walls), it will wet the entire tank surface to minimize the surface energy at the walls. In addition, the shape of the gas bubble in the tank center will have a minimum surface area in order to minimize the surface energy of liquid to gas.

The stable configuration of a wetting fluid in a container will be identical to any other wetting fluid in the same container if the liquid volumes are the same. The reason is that the minimum energy of any wetting fluid is dependent upon the tank geometry and liquid to gas volume ratios only. If we now maintain geometric similarity by using a scale model tank and have the liquid to gas volume ratio of test fluid equal that ratio in the Centaur, a model test using any wetting fluid will result in a liquid distribution exactly similar to what will occur in the Centaur during zero-g.

Because any wetting liquid will satisfy the coalescence tests, it is recommended that a high reaction rate liquid be used. A liquid with a high reaction rate is defined here as one that will approach its equilibrium configuration rapidly. Since the expected time in zero-g for the model test will be approximately 7 to 15 seconds, and since a near equilibrium liquid distribution is desired during the zero-g period, time is an important factor. Drop tests, that produce approximately one second of zero-g will be conducted with a number of liquids in order to select a high reaction rate liquid for the KC-135 tests.

The transient behavior of liquid as it advances to its equilibrium distribution is also of interest, since a knowledge of the approximate time to reach propellant equilibrium in the Centaur tank would permit a more intelligent evaluation of the coalescing surfaces and interpretation of the heat transfer data to be collected during the coast periods. This transient period is too complex to be described analytically with our present knowledge of fluid motion in zero-g. However, time to reach equilibrium may be predicted from the test sequence that follows:

1. Liquid hydrogen and a high reaction rate liquid will be tested in the same size container and their rate of progress towards equilibrium compared.

2. The second fluid will be tested in a larger, geometrically similar container, and its reaction rates for both containers compared. (Possibly drop tests with a smaller container will be of sufficient duration to provide a third value.)

3. The reaction rate ratio between liquids and between geometrically similar containers of different size will permit extrapolation of the results with hydrogen to the actual Centaur case. Hopefully, this extrapolation will support theoretical predictions which will be attempted.

The use of a second fluid will permit the utilization of a large container. At present, no authorization has been given by WADD to use liquid hydrogen in a large container. The reason is that, should capsule failure and bag rupture occur concurrently, the amount of liquid hydrogen in the bag should not exceed 3.5 liters if its concentration is to remain below allowable limits.

Settling Tests: The settling tests are for the purpose of determining, from model testing, the time required to settle propellants in the Centaur prior to each of its engine starts.

The liquid in the Centaur tank prior to settling can be distributed in many ways. Two extremes shown in Figures 1 and 2 are, liquid distributed in droplet form, and liquid wetting the walls. Applying the equation of motion to the liquid in each of the distributions, one is able to arrive at the governing parameters.

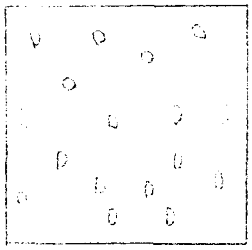

Figure 1

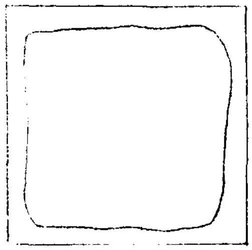

Figure 2

Application of the equation of motion to a falling spherical droplet yields

$$m \frac{dv}{dt} = ma - C_d q A \qquad (1)$$

where m =	mass of droplet	$\frac{lb.sec^2}{ft}$
$\frac{dv}{dt}$ =	acceleration of droplet	ft/sec^2
a =	applied acceleration	ft/sec^2
C_d =	droplet drag coefficent	———
q =	droplet velocity pressure	psi
A =	droplet cross-sectional area	in^2

It was computed that droplets one inch or more in diameter will be acted upon by drag forces that are 10% or less of the applied acceleration forces during settling. Furthermore it is estimated that most drops will be one inch or larger. Because a 10% error can be tolerated, the drag term will be dropped from equation (1) and we have,

$$m \frac{dv}{dt} = ma \qquad (2)$$

Equation (2) shows that fluid properties will not affect settling times of propellants. Therefore, Centaur fuel settling can be simulated with any liquid so long as geometric similarity is achieved.

Applying the equation of motion to the case where liquid is wetting the walls an additional force term, which includes the effect of surface tension, is added to equation (1).

$$m \frac{dv}{dt} = ma - C_d q A - \sigma (\pi D) \qquad (3)$$

where D = tank diameter in.

σ = surface tension lb/in

Equation (3) describes settling of liquid flowing along the tank walls with surface tension forces opposing the fluid motion.

It will be shown that surface tension forces will be very small in the Centaur and can be ignored for any settling simulation study. Surface tension forces opposing liquid flow along the walls during LH_2 settling in the Centaur are equal to the product of surface tension and tank circumference. $\sigma(\pi D)$ = .004 lb. For the second start the acceleration forces that are settling the approximate 1200 lb. of LH_2, are $ma = \left(\frac{1200}{32.2}\right)(0.5) = 18.6$ lb.

Thus it is seen that surface tension forces are insignificant during Centaur fuel settling. Although the magnitude of the surface tension to acceleration forces will be increased in the model tests, surface tension forces will still be insignificant.

If the drag term of equation (3) is also left out, as before, because the drag forces are small compared to acceleration forces, equation (3) becomes identical to equation (2).

Since fluid properties will not affect propellant settling, equation (2) can be used to compute LH_2 settling times in the Centaur, Therefore only a few settling tests will be performed to substantiate computations; they will be combined with the sloshing tests. It is possible to combine settling with sloshing tests because the initial phase of the sloshing tests requires propellant settling. It is only after liquid has been accelerated to one end of the tank that sloshing can be observed.

Sloshing Tests: The tank model sloshing tests, if properly simulated, will indicate if sloshing in the Centaur fuel tank during settling will be a problem.

An analysis of the propriety of simulating Centaur fuel sloshing by testing with a model has been performed. The approach taken was to non-dimensionalize the generalized continuity and momentum equations. The process yielded three dimensionless numbers that by the laws of similarity must be the same for the model test as for the Centaur. These numbers were the Froude, Weber, and Reynolds numbers.

It appears that similarity with all three dimensionless numbers is not possible because a liquid with suitable properties cannot be found. Viscosity effects have always been neglected in theoretical analyses on sloshing. This is equivalent to neglecting the influence of Reynold number. Therefore only Froude and Weber numbers will be simulated in the model tests.

Using liquid properties and tank acceleration of the model test as variables an attempt was made to determine which combination of liquid and acceleration would not only satisfy the dimensionless numbers, but be suitable for the airplane tests. Since testing will be performed in confined spaces the tank acceleration should be a minimum. Results of an analysis showed that using liquid nitrogen as a test fluid will result in the minimum tank acceleration of 0.20 g's. Therefore it is suggested that LN_2 be used as the fluid for sloshing tests.

Test results will show the time required for liquid damping to occur.

References:

1. Convair Report AE60-0682
2. Convair Report AE60-0942